Experience with polarized proton acceleration at COSY (Jülich)

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Abstract: A concept has been developed and realized to accelerate vertically polarized protons in the COoler SYnchrotron COSY at the Forschungszentrum Jülich up to the maximum momentum of 3300 MeV/c [1].

1 Introduction

The COoler SYnchrotron and storage ring COSY at the Forschungszentrum Jülich accelerates protons to momenta between 600 MeV/c and 3300 MeV/c [2]. At present the beam is used at four internal and three external target places. In addition, a polarized beam can be produced and accelerated at COSY. A colliding beams source, developed by a collaboration of the universities of Bonn, Erlangen, and Cologne is in operation [3]. The polarized H^- beam delivered by this source is pre-accelerated in a cyclotron to 295 MeV/c and injected via stripping injection into the COSY ring. The polarization of the circulating proton beam in COSY is measured continuously during acceleration with the internal EDDA detector [4]. In this paper the methods to overcome depolarizing resonances in COSY are discussed and the progress to preserve polarization during acceleration is presented.

2 Depolarizing resonances

For an ideal planar circular accelerator with a vertical guide field like COSY, the particle spin vector precesses around the vertical axis. Thus the vertical beam polarization is preserved. The number of spin precessions per revolution of the beam in the ring is given by $\nu_{sp} = \gamma G$ [5], where $G = 1.7928$ is the proton anomalous magnetic moment and γ is the Lorentz factor. During acceleration of a polarized beam, depolarizing resonances are crossed if the precession frequency γG of the spin is equal to the frequency of the encountered spin-perturbing magnetic fields. A strong-focusing synchrotron has two different types of strong depolarizing resonances, namely imperfection resonances caused by magnetic field errors and misalignments of the magnets and intrinsic resonances excited by horizontal fields due to the vertical focusing.

2.1 Imperfection Resonances at COSY

In the energy range of COSY five imperfection resonances have to be crossed. The resonance strength depends on the vertical closed orbit deviation. Without correcting the vertical orbit, the spin is flipped at each imperfection resonance (Table 1). To calculate the polarization

Table 1: *Resonance strength ϵ_r of imperfection resonances and ratio of preserved polarization P_f/P_i for an energy gain per turn of 0.7 keV and a typical vertical orbit deviation y_{co}^{rms} at the various resonance energies, without considering synchrotron oscillation.*

γG	E_{kin} (MeV)	p (MeV/c)	y_{co}^{rms} (mm)	ϵ_r (10^{-3})	P_f/P_i
2	108.4	463.8	2.3	0.95	-1.00
3	631.8	1258.7	1.8	0.61	-0.88
4	1155.1	1871.2	1.6	0.96	-1.00
5	1678.5	2442.6	1.6	0.90	-1.00
6	2201.8	2996.4	1.4	0.46	-0.58

losses during resonance crossing, the influence of synchrotron oscillation cannot be neglected at COSY (Fig. 1) [6]. The resonance strength of the first imperfection resonances has to be
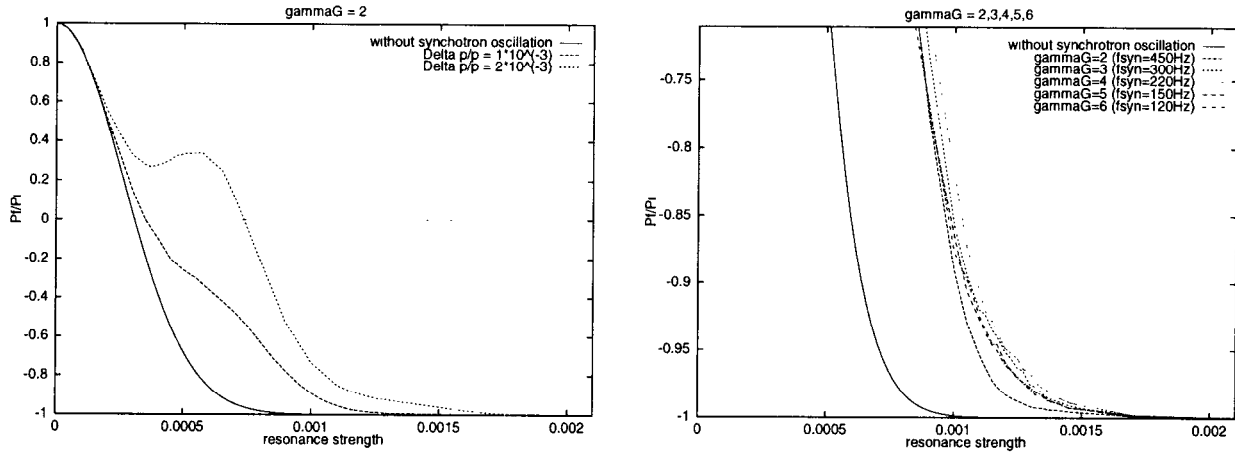

Figure 1: *Effect of synchrotron oscillation during crossing imperfection resonances in COSY. Ratio of preserved beam polarization P_f/P_i after crossing the first imperfection resonance for several momentum spreads and a synchrotron tune of $f_{syn} = 450Hz$ (left) and after crossing different imperfection resonances for a momentum spread of $\Delta p/p = 1 \cdot 10^{-3}$ taking the synchrotron tunes at the various resonance energies into account (right).*

enhanced to $1.6 \cdot 10^{-3}$ for a beam with momentum spread of $\Delta p/p = 2 \cdot 10^{-3}$ to excite spin flips with polarization losses of less than 1%. At the other imperfection resonances the effect of the synchrotron oscillation is smaller, due to lower momentum spread at higher energies. Simulations indicate that an excitation of the vertical orbit by 1 mrad using the existing vertical correcting dipoles is sufficient to adiabatically flip the spin at all imperfection resonances. In addition, the solenoids of the electron cooler system inside COSY are available for use as a partial snake. They are able to rotate the spin around the longitudinal axis by about 8° at the

maximum momentum of COSY. A rotation angle of less than 1° of the spin in a partial snake already leads to a spin flip without polarization losses at all five the imperfection resonances.

2.2 Intrinsic Resonances at COSY

The number of intrinsic resonances depends on the superperiodicity P of the lattice, which is given by the number of identical periods of the accelerator. COSY is a synchrotron with a racetrack design consisting of two 180° arc sections connected by straight sections. The straight sections can be tuned as telescopes with 1:1 imaging, giving a 2π phase advance. Both arcs are composed of three unit cells which are each mirror-symmetrical. A half-cell has a QD-bend-QF-bend structure. When the betatron phase advance in the two straight sections of COSY is matched to 2π, these sections are optically transparent and only the arcs contribute to the strength of intrinsic resonances. One obtains for the resonance condition $\gamma G = k \cdot P \pm (\nu_y - 2)$, where k is an integer and ν_y is the vertical betatron tune. The magnetic structure in the arcs allows adjustment of the superperiodicity to $P = 2$ or 6. The corresponding intrinsic resonances in the momentum range of COSY are listed in Table 2. The superperiodicity equals 6 if all unit

Table 2: *Resonance strengths ϵ_r of intrinsic resonances for a normalized emittance of 1π mm mrad and a vertical working point of 3.61 for different superperiodicities P.*

P	γG	E_{kin} (MeV)	p (MeV/c)	ϵ_r (10^{-3})
2	$6 - \nu_y$	312.4	826.9	0.26
2	$0 + \nu_y$	950.7	1639.3	0.21
2,6	$8 - \nu_y$	1358.8	2096.5	1.57
2	$2 + \nu_y$	1997.1	2781.2	0.53
2	$10 - \nu_y$	2405.2	3208.9	0.25

cells are operated with the same quadrupole settings. In this case only one intrinsic resonance occurs, $\gamma G = 8 - \nu_y$, but the transition crossing takes place at about 1600 MeV/c. To accelerate the beam to maximum momentum, the strength of the horizontally focusing quadrupoles in the inner unit cells is enhanced by about 40% to shift the transition energy above the maximum momentum. At the same time, the strength of the horizontally focusing quadrupoles in the outer unit cells is decreased by 20% to keep the betatron tunes constant. The superperiodicity of such a beam optics is 2. Consequently, four additional intrinsic resonances are introduced (Table 2), which can be suppressed if the harmonics of the corresponding spin-perturbing fields are corrected. Theoretical studies of the COSY lattice revealed the possibility of suppressing the strength of intrinsic resonances using the vertically focusing quadrupoles in the inner unit (Fig. 2) [7].

For the remaining intrinsic resonances the technique of tune jumping is used. A tune jump allows one to preserve polarization at intrinsic resonances by increasing the crossing speed significantly. This is accomplished by abruptly changing the vertical betatron tune during resonance crossing in the range of microseconds. A magnet system consisting of two pulsed air core quadrupoles was developed. This system was designed to achieve polarization losses of less than 5% at the strongest intrinsic resonance, and less than 1% at all other intrinsic resonances
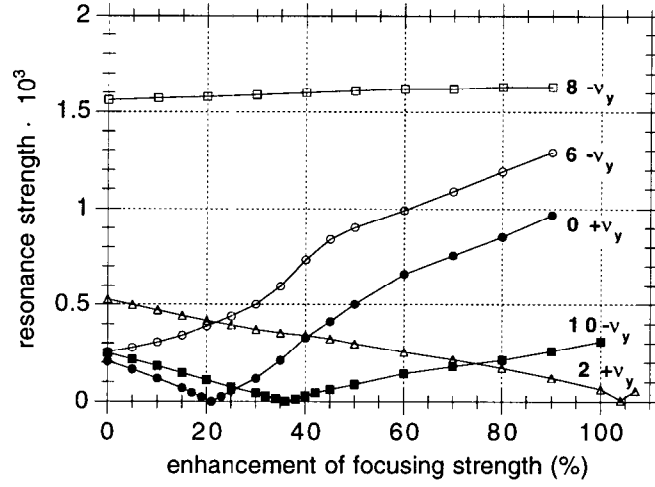
Figure 2: *Resonance strength of depolarizing resonances in case of a P=2-optics versus the enhancement of focusing strength of the vertically focusing quadrupoles in the inner unit cells. The betatron tune is fixed by reducing the strength of the vertically focusing quadrupoles in the outer unit cells. In this calculation the focusing strength of the horizontally focusing quadrupoles in the inner unit cells is enhanced by about 40%.*

in COSY [8]. To meet this goal, a vertical tune jump of 0.06 in $10\mu s$ was needed. Fig. 3 shows the polarization of the COSY beam measured during acceleration around the strongest intrinsic resonance $\gamma G = 8 - \nu_y$.
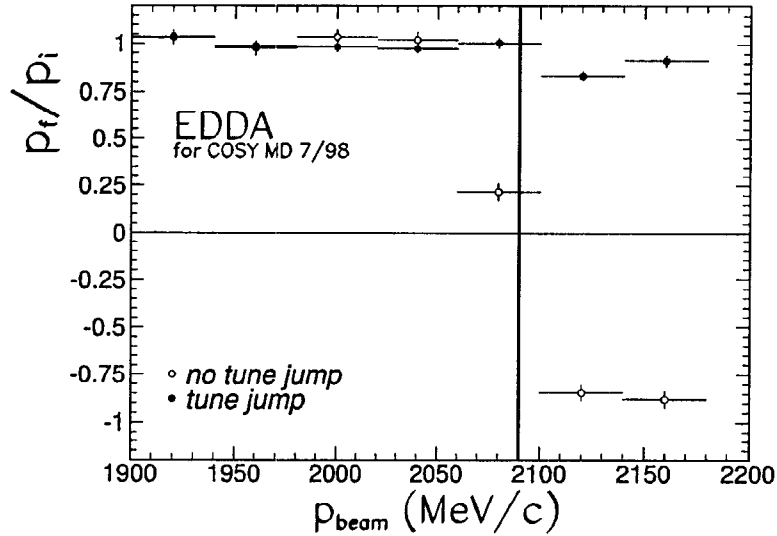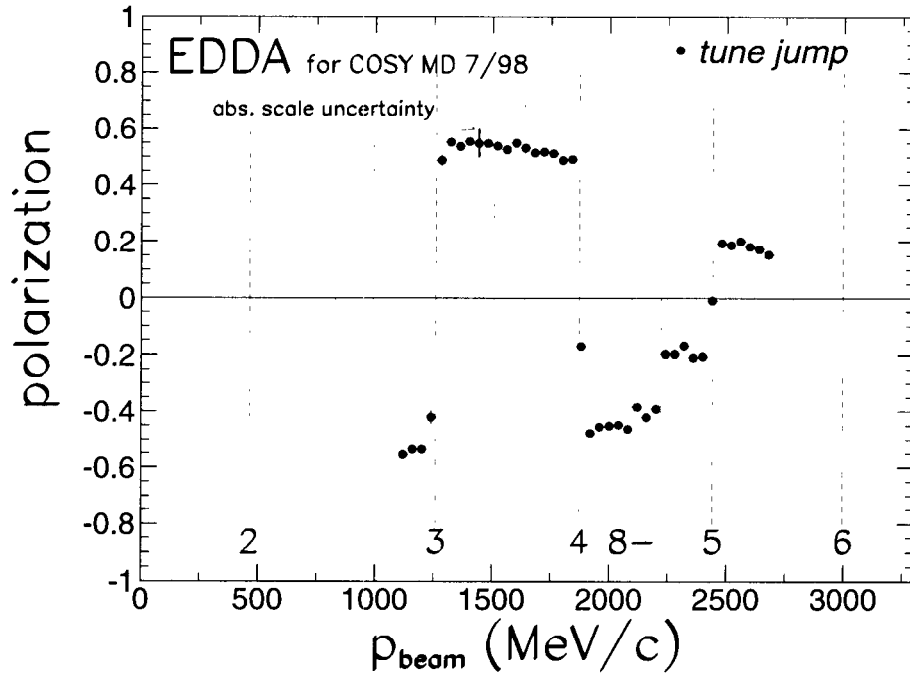

Figure 3: *Ratio of preserved beam polarization P_f/P_i after crossing the strongest intrinsic resonance at 2090 MeV/c with and without tune jump measured during acceleration.*

This resonance excites a natural spin flip. The polarization loss depends on the vertical emittance of the beam. With a tune jump, the polarization was almost preserved. This tune jump method can be extended to all other intrinsic resonances because they are nearly a factor three weaker than the strongest resonance.

3 Acceleration of the polarized beam

During the July 1998 running period, the polarized beam was accelerated to 2700 MeV/c. The spin was flipped at the imperfection resonances $\gamma G = 2, 3, 4$ and 5 using correcting dipoles. At the first imperfection resonance also the partial snake has already been applied to preserve polarization [9]. To avoid polarization losses at the first intrinsic resonance, $\gamma G = 6 - \nu_y$ at 827 MeV/c, the acceleration of the beam started with P=6 optics. At about 900 MeV/c, the COSY beam optics was then switched to superperiodicity P=2 to shift the transition energy. As expected, crossing $\gamma G = 0 + \nu_y$ at 1640 MeV/c led to polarization losses. After suppressing the strength of intrinsic resonances using the vertically focusing quadrupoles in the inner unit, the ratio of the preserved polarization at the second intrinsic resonance could be significantly increased [7]. At the strongest intrinsic resonance, the polarization could be almost preserved using a tune jump. The measured polarization after this optimization for polarized beam is shown in Fig. 4. Some polarization losses at the resonance $\gamma G = 1 + \nu_y$ at about 2220 MeV/c

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Figure 4: *Beam polarization measured during acceleration with the EDDA detector in the momentum range between 1100 MeV/c and 2700 MeV/c.*

could be observed, which only occurs at a P=1-optics. This indicates that the optics of the straight sections has to be readjusted at higher energies. In the following running period in

December 1998 tune jumps were used to cross intrinsic resonances above 2700 MeV/c. We were able to preserve polarization up to the maximum momentum of COSY.

4 Conclusion

Correction dipoles and the solenoids of the electron cooler acting as a partial snake were successfully used to preserve the polarization by exciting adiabatic spin flips. Both methods are available for all five imperfection resonances in the momentum range of COSY. With the standard optics of COSY, five intrinsic resonances are excited. Calculations predict, and measurements confirm, that some of these resonances can be suppressed by changing the optics during acceleration. For the remaining intrinsic resonances the method of tune jumping is used. A magnet system consisting of two pulsed air core quadrupoles was developed and successfully applied at the strongest intrinsic resonance to preserve polarization. Polarization measurements during acceleration confirm that the developed concept allows the acceleration of a vertically polarized proton beam up to the maximum momentum of COSY.

5 Acknowledgement

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